Soft Contribution to Quark-Quark Scattering Induced by an Anomalous Chromomagnetic Interaction

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Abstract

We calculate the soft contribution to high energy quark-quark scattering that arises from an instanton-induced quark anomalous chromomagnetic moment. We demonstrate that this is a large contribution, which cannot be neglected for transverse momenta of a few GeV. We discuss the influence of this effect on inclusive particle production.

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1 Introduction

The theoretical interpretation of the precise data now available on inclusive particle production is one of the central problems of QCD. These data provide important information on the nature of the strong interaction between quarks and gluons for a range of scattering kinematics, and their interpretation is very useful for a more complete understanding of QCD. Furthermore, inclusive particle production data is used as a baseline for the interpretation of more complicated experimental data, such as secondary particle correlations, spin asymmetries, and so forth. One specific area of particular interest is the possibility of studying the properties of quark-gluon matter produced in heavy ion collisions at RHIC, through the use of inclusive particle production rates.

One of the main components of perturbative QCD (pQCD) calculations of inclusive rates is the set of perturbative partonic cross sections. However, it has been found that the use of the leading-twist partonic cross sections in successive orders of the strong coupling constant α_s (LO, NLO, etc.) does not lead to a satisfactory description of the available high energy inclusive data over the broad kinematical range where pQCD is expected to be applicable [1, 2, 3]. One possible resolution of this discrepancy is to include the effects of intrinsic parton transverse momentum distributions. (For a recent discussion see Ref.[4].) This approach allows one to incorporate higher-twist corrections to pQCD predictions for the inclusive rates in the context of a specific phenomenological model of transverse momenta.

Unfortunately, the non-zero intrinsic transverse momenta of the initial partons implies the loss of the advantages of collinear pQCD calculations. Furthermore, it is difficult to justify the large value of the average intrinsic transverse momentum of partons in the nucleon which is required to fit the inclusive data, $< k_\perp > \approx 1$ GeV. This large value disagrees with the scale of $< k_\perp > \approx 200$ MeV $\approx 1/R_{conf}$ one would expect if the origin of the intrinsic momentum was simply confinement.

Here we consider another important higher-twist contribution to partonic cross sections, which is related to the topological structure of the QCD vacuum. It is well known that the QCD vacuum has a rich spectrum of gluon field fluctuations, with different length and momentum scales. One type of long-range gluonic excitations, for example, is responsible for confinement. Another important category includes the strong topological fluctuations known as instantons; these play significant roles in hadron physics, such as providing a mechanism for chiral and $U(1)_A$ symmetry violations [5, 6].

Instantons have a small typical size of $\rho_c \approx 0.3$ fm, and can therefore provide higher-twist contributions which remain significant at the momentum transfers considered here. In particular, instantons lead to a nonperturbative anomalous chromomagnetic quark-gluon vertex, which is not encountered in conventional pQCD [6, 7]. In this letter we demonstrate that the contribution of this quark anomalous chromomagnetic moment to high energy quark-quark scattering is large in this kinematic regime, and is therefore an interesting candidate for the fundamental QCD mechanism underlying the important higher-twist effects observed in inclusive particle production.

2 Chromomagnetic contribution to quark-quark scattering

The effective chromomagnetic quark-gluon interaction induced by instantons is given by [6, 7]

$$\mathcal{L}_{eff} = -i\frac{g_s\mu_a}{2M_q}\bar{q}\sigma_{\mu\nu}t^a G^a_{\mu\nu}q, \tag{1}$$

where μ_a is the quark anomalous chromomagnetic moment, M_q is the effective quark mass in the instanton vacuum, and $G^a_{\mu\nu}$ is the gluon field strength tensor. For an off-shell gluon of virtuality q, the instanton-induced quark-gluon vertex of (1) should be multiplied by the instanton form factor

$$F(z) = \frac{4}{z^2} - 2K_2(z), \tag{2}$$

where $z = q\rho_c$. The value of the quark anomalous chromomagnetic moment is proportional to the instanton packing fraction in the QCD vacuum, $f = n_c\pi^2\rho_c^4 \approx 0.1$, where n_c is the instanton density.

The diagram which gives the instanton contribution to quark-quark scattering in the high energy limit ($s >> |t|$) due to the interaction (1), at leading order in the instanton packing fraction, is shown in Fig.1. (Here, $s = (p_1+p_2)^2$ and $t = (p_1-p_3)^2$.) A straightforward calculation gives the resulting differential cross section,

$$\frac{d\sigma^{chrom}}{dt} = \frac{2\mu_a^2|t|(F(\sqrt{|t|}\rho_c))^2}{M_q^2}\frac{d\sigma^{pert}}{dt} \tag{3}$$

where

$$\frac{d\sigma^{pert}}{dt} = \frac{8\pi\alpha_s(t)}{9t^2} \tag{4}$$

is the LO one-gluon pQCD cross section.

In Fig.2 we compare the pQCD (one-gluon exchange) and nonperturbative chromomagnetic results for the elastic quark-quark scattering cross section as a function of transverse momentum, for the special case of 90° scattering ($p_\perp = \sqrt{-t/2}$). We assume a value of

$$\mu_a = -0.744, \tag{5}$$

for the quark anomalous chromomagnetic moment, which was obtained in Ref.[6] for the case $N_f = 3$. [1] We also assume a constituent quark mass of $M_q = 350$ MeV, and an instanton inverse length scale of ${\rho_c}^{-1} = 600$ MeV; these are typical of the values used in the instanton liquid model [5, 6]. For the strong coupling constant, the following parametrization was used for the case $N_f = 3$;

$$\alpha_s(t) = \frac{4\pi}{9\ln((|t|+4m_g^2)/\Lambda^2)}, \tag{6}$$

where $m_g^2 = 0.2$ GeV^2 and $\Lambda = 0.16$ GeV [8]. One can see in Fig.2 that this nonperturbative contribution is quite large, and exceeds the pQCD result for transverse momenta

[1] In the calculation of the instanton-induced quark anomalous chromomagnetic moment reported in Ref.[7] for the case $N_f = 1$, a much smaller value of $\mu_a \approx -0.2$ was found.

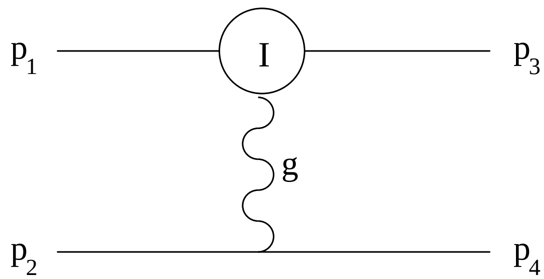

Figure 1: The Feynman diagram representing the contribution of the quark chromomagnetic moment to high energy quark-quark scattering.

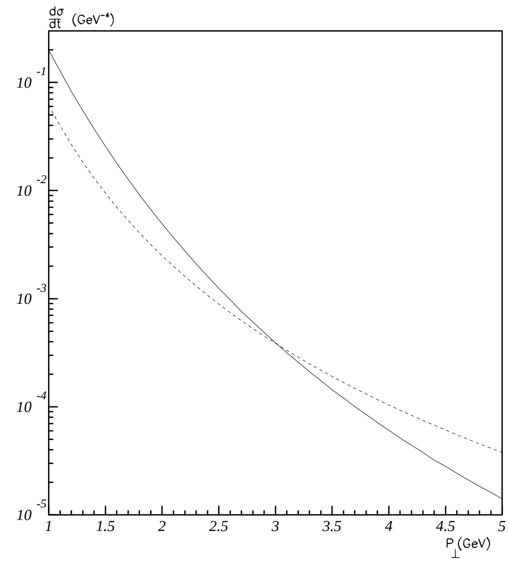

Figure 2: Perturbative (dashed) and non-perturbative (solid) quark-quark differential cross sections versus transverse momentum.

of $p_\perp < 3$ GeV. This suggests that the pQCD regime is only encountered at rather larger values of $p_\perp$.

The asymptotic behaviour of the nonperturbative contribution for large $p_\perp$ is determined by the instanton form factor (2),

$$\frac{d\sigma^{chrom}}{dp_\perp} \approx \frac{A}{p_\perp^6}, \tag{7}$$

where A is a constant. This $p_\perp$ dependence is steeper than is predicted by leading-twist pQCD, which anticipates $1/p_\perp^4$. We note in passing that the value $n^{chrom} = 6$ in (7) is in agreement with the result $n_{eff} = 6.33 \pm 0.54$ found in the recent analysis of RHIC data on inclusive neutral pion production in peripheral heavy ion collisions [9]. (See also the discussion in Ref.[3].) Thus it appears that this nonperturbative scattering mechanism may also provide a viable explanation for the recent RHIC inclusive pion production data.

3 Conclusion

We have discussed a novel nonperturbative, instanton-based contribution to quark-quark scattering at high energies. This scattering mechanism is due to the existence of a quark anomalous chromomagnetic moment, which originates from the instanton structure of the QCD vacuum. We have shown that this new soft contribution to the partonic cross section is numerically rather large in the kinematic regime considered, and may be responsible for the discrepancy between leading-twist pQCD predictions and the existing high energy data on inclusive particle production. We should also emphasize that due to its strong helicity dependence, a large contribution coming from an anomalous chromomagnetic interaction to a single spin [7, 10] as well to a double spin asymmetries is expected.

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